

On the orbit of the short-period exoplanet WASP-19b

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ABSTRACT

WASP-19b has the shortest orbital period of any known exoplanet, orbiting at only 1.2 times the Roche tidal radius. By observing the Rossiter–McLaughlin effect we show that WASP-19b’s orbit is aligned, with $\lambda = 4.6 \pm 5.2^\circ$. Using, in addition, a spectroscopic $v \sin I$ and the observed rotation period we conclude that the obliquity, ψ , is less than 20° . Further, the eccentricity of the orbit is less than 0.02. We argue that hot Jupiters with orbital periods as short as that of WASP-19b are two orders of magnitude less common than hot Jupiters at the 3–4-d ‘pileup’. We discuss the evolution of WASP-19b’s orbit and argue that most likely it was first moved to near twice the Roche limit by third-body interactions, and has since spiralled inwards to its current location under tidal decay. This is compatible with a stellar tidal-dissipation quality factor, Q'_* , of order 10^7 .

Subject headings: stars: individual (WASP-19) — planetary systems

1. Introduction

Of the known transiting exoplanets WASP-19b has the shortest orbital period, at only 0.79 d, and thus is important for constraining models of the orbital evolution of hot-Jupiter planets. This area of theory is currently undergoing rapid development owing to the finding of planets with apparently short dynamical lifetimes owing to strong tidal interactions with their host stars (e.g. Rasio et al. 1996; Levrard, Winisdoerffer & Chabrier 2009; Matsumura, Peale & Rasio 2010; Penev & Sasselov 2011), of which WASP-18b (Hellier et al. 2009) and WASP-19b (Hebb et al. 2010) are among the most extreme.

Further, many of the orbits of hot Jupiters are being found to be misaligned with the stellar spin axis, with some being retrograde (e.g. Winn et al. 2009; Narita et al. 2009; Triaud et al. 2010), which cannot be accounted for solely by the ‘migration’

scenario (e.g. Lin et al. 1996) in which hot Jupiters form further out and migrate through a protoplanetary disc to short-period orbits.

Thus a picture is emerging in which hot-Jupiter orbits result from a mixture of processes including: disc migration; planet–planet scattering and the Kozai mechanism, by which planets can be driven into eccentric or misaligned orbits through the influence of a third perturbing body; and tidal dissipation, which circularises and shortens orbits (e.g. Fabrycky & Tremaine 2007; Nagasawa, Ida & Bessho 2008; Matsumura et al. 2010; Naoz et al. 2010).

The relative importance of these mechanisms for the ensemble of hot Jupiters can be investigated particularly by using the transiting exoplanets (e.g. Triaud et al. 2010; Morton & Johnson 2011), since the Rossiter–McLaughlin effect (a distortion of the star’s line profiles as the planet transits the stellar disc) tells us the angle between the planetary orbit and the sky-projection of the stellar spin axis.

Ford & Rasio (2006) pointed out that the orbital period distribution of hot Jupiters cuts off near 2 Roche radii, which could be explained if planets are scattered into highly elliptical orbits

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from much further out and then circularise while conserving angular momentum (in contrast, disc migration alone would predict a smooth distribution down to the Roche limit).

WASP-19b is one of a small number of planets with substantially smaller orbital radii, and is the most extreme at only 1.2 times the Roche limit. Guillochon, Ramirez-Ruiz & Lin (2010) argue that it would be hard to scatter a planet into such an orbit, since it would instead be destroyed or ejected, and argue that either disc migration prior to scattering or tidal decay of the orbit after scattering is also necessary.

We report here an observation of the Rossiter–McLaughlin (R–M) effect for WASP-19b, which we analyse along with other data to further constrain WASP-19b’s orbit, and discuss how this planet fits into the above theoretical picture.

2. Observations

We obtained 25 spectra of WASP-19 through a transit on 2010 March 19 using the HARPS spectrograph on the ESO 3.6-m at La Silla. The data were reduced using the Data Reduction Software by removing the blaze function and cross-correlating with a G2 mask (see Triaud et al. 2010 for further details). In addition 2 HARPS spectra were taken two days earlier and 3 more over the next two days to better constrain the in-transit data. We also report 6 more HARPS spectra and 3 spectra from the CORALIE spectrograph on the Swiss Euler 1.2-m telescope obtained to tie down the eccentricity of the orbit (the 39 new radial velocities are listed in Table 1). In the following analysis we also include the 34 CORALIE radial velocities previously listed by Hebb et al. (2010).

To constrain the transit time, duration and ingress and egress lengths, thus improving the R–M analysis, we included a photometric Gunn r -band transit obtained using the ESO NTT/EFOSC on the night of 2010 February 28, 19 days from the HARPS transit. The telescope was defocused so that each PSF covered approximately 8500 pixels. The data were reduced using aperture photometry relative to an optimal combination of six comparison stars following the methods of Southworth et al. (2009). We also included 17 162 WASP-South photometric data points from 2006–2008 and the FTS z -band lightcurve reported by Hebb

Table 1: Radial velocity measurements of WASP-19. The first three are from CORALIE and the remainder from HARPS.

BJD–2 400 000	RV (km s ^{−1})	σ_{RV} (km s ^{−1})	BS (km s ^{−1})
54972.4982	20.8874	0.0176	0.0066
54973.4648	20.6042	0.0182	−0.0806
54999.4857	20.5571	0.0341	0.0223
55242.6884	20.7469	0.0036	−0.0074
55242.8457	21.0203	0.0050	−0.0197
55243.6590	21.0391	0.0042	0.0116
55243.8242	20.9547	0.0043	0.0213
55244.7221	20.7355	0.0031	0.0081
55247.7151	21.0254	0.0088	0.0202
55272.5445	20.5741	0.0044	−0.0180
55272.7776	20.9778	0.0052	−0.0280
55274.5328	21.0391	0.0073	0.0056
55274.6147	20.9318	0.0124	−0.0369
55274.6224	20.9129	0.0112	−0.0573
55274.6299	20.8819	0.0094	−0.0486
55274.6375	20.8842	0.0088	0.0044
55274.6451	20.8711	0.0084	−0.0122
55274.6525	20.8914	0.0086	0.0135
55274.6602	20.8473	0.0094	−0.0158
55274.6679	20.8214	0.0100	0.0340
55274.6754	20.7819	0.0108	0.0141
55274.6830	20.7568	0.0118	0.0626
55274.6907	20.7315	0.0108	−0.0030
55274.6983	20.7138	0.0103	0.0136
55274.7058	20.7262	0.0106	0.0147
55274.7134	20.7093	0.0104	−0.0431
55274.7210	20.7151	0.0118	−0.0090
55274.7288	20.7056	0.0120	−0.0379
55274.7363	20.6582	0.0116	0.0071
55274.7438	20.6687	0.0104	−0.0343
55274.7514	20.6387	0.0119	0.0095
55274.7591	20.6452	0.0113	−0.0058
55274.7667	20.6136	0.0105	−0.0057
55274.7740	20.6079	0.0106	−0.0005
55274.7818	20.5771	0.0123	0.0043
55274.8216	20.5707	0.0069	−0.0187
55275.5221	20.6841	0.0052	−0.0226
55275.7895	20.6841	0.0077	−0.0016
55276.5146	20.5850	0.0062	0.0018

Bisector errors are twice RV errors

et al. (2010).

The time of secondary occultation (of the planet by the star) helps to tie down the eccentricity, and thus we included in our analysis the H -band occultation photometry reported by Anderson et al. (2010), detrending it with a quadratic function of time and sky-background, as in that paper, and also the K -band data of Gibson et al. (2010), with a linear detrending in time.

3. Analysis

To model WASP-19b's orbit we used a Markov Chain Monte Carlo (MCMC) approach similar to that used by Triaud et al. (2010) and based on an R-M model code described more fully in Triaud et al. (2009). The datasets listed in the previous section were fitted simultaneously with a model based on the parameters T_c , P , ΔF , T_{14} , b , K_1 , T_{eff} , $[\text{Fe}/\text{H}]$, $\sqrt{e} \cos \omega$, $\sqrt{e} \sin \omega$, $\sqrt{v \sin I} \cos \lambda$, $\sqrt{v \sin I} \sin \lambda$, and, for the occultation data, $\Delta F_{1.6 \mu\text{m}}$ and $\Delta F_{2.09 \mu\text{m}}$. Here, T_c is the epoch of mid-transit, P is the orbital period, ΔF is the fractional flux-deficit that would be observed during transit in the absence of limb-darkening, T_{14} is the total transit duration (from first to fourth contact), b is the impact parameter of the planet's path across the stellar disc, K_1 is the stellar reflex velocity semi-amplitude, T_{eff} is the stellar effective temperature, $[\text{Fe}/\text{H}]$ is the stellar metallicity, e is the orbital eccentricity, ω is the argument of periastron, and $\Delta F_{1.6 \mu\text{m}}$ and $\Delta F_{2.09 \mu\text{m}}$ are the planet/star flux ratios at $1.6 \mu\text{m}$ and $2.09 \mu\text{m}$ respectively. The resulting system parameters are listed in Table 2 and the model fits are illustrated in Figure 1.

As inputs to the MCMC we used Gaussian “priors” of $T_{\text{eff}} = 5500 \pm 100$ K and $[\text{Fe}/\text{H}] = 0.02 \pm 0.09$ (from Hebb et al. 2010). We also applied a prior on $v \sin I$ of $5.0 \pm 0.3 \text{ km s}^{-1}$ (where we use $v \sin I$ for the projected stellar rotation to distinguish from i as the inclination of the planet's orbit). This was estimated from the HARPS spectra by fitting the profiles of several unblended Fe I lines. We measured an instrumental broadening of 0.06 \AA from telluric lines and we assumed a value for macroturbulence of $1.7 \pm 0.3 \text{ km s}^{-1}$ (Bruntt et al. 2010).

As discussed by Triaud et al. (2011) the choice of $v \sin I$ prior is critical in modelling the R-M ef-

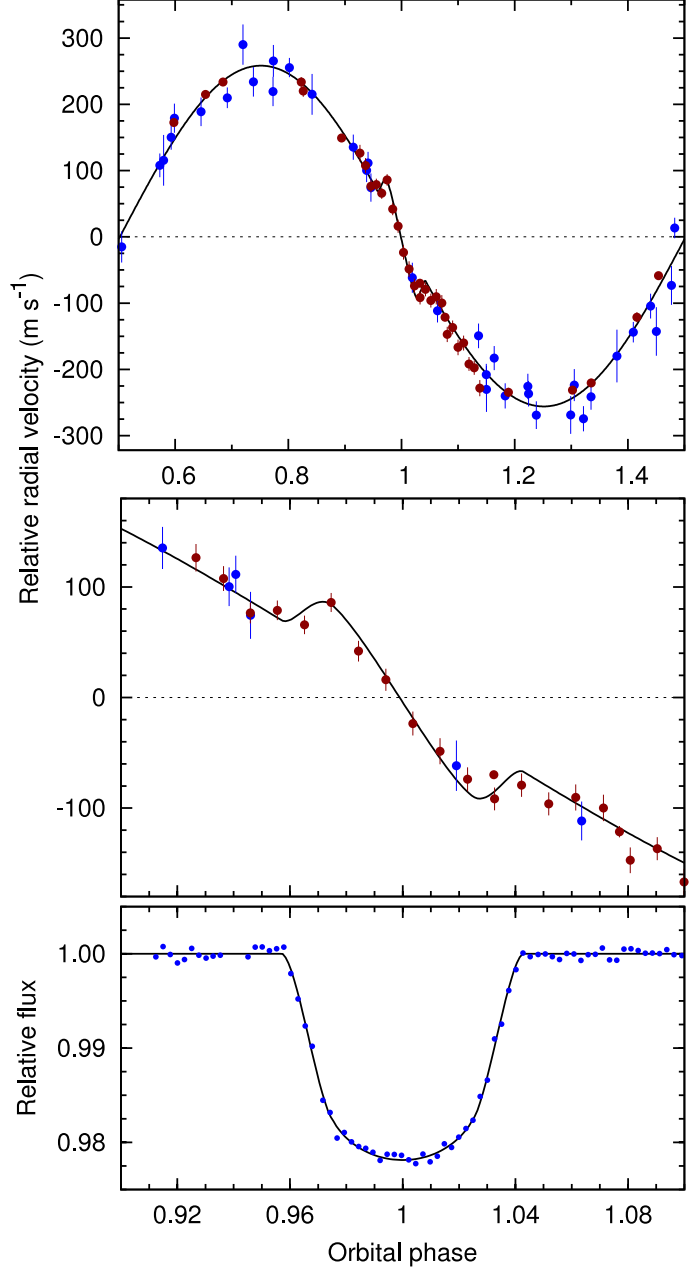


Fig. 1.— (Top) The HARPS (brown) and CORALIE (blue) radial velocities of WASP-19 together with the fitted model. (Second panel) The transit region shown expanded. (Lower panel) The NTT transit lightcurve and fitted model.

fect when the planet has a low impact parameter. This is because an orbit at right-angles to the spin axis and with zero impact parameter is insensitive to $v \sin I$. However, for WASP-19b the impact parameter ($b = 0.66 \pm 0.02$) is high enough to remove the degeneracy, and omitting the prior makes little difference (the R–M angle, λ , is $4.6 \pm 5.2^\circ$ with the $v \sin I$ prior and $6.2 \pm 6.8^\circ$ without).

The stellar T_{eff} , along with the stellar density and metallicity, was propagated to the stellar mass using the calibration of Enoch et al. (2010). T_{eff} was also used to select limb-darkening coefficients from the four-parameter models listed by Claret (2000; 2004). We also added jitter of 14.1 m s^{-1} to the CORALIE radial velocities and 6.9 m s^{-1} to the HARPS radial velocities in order to obtain a spectroscopic χ^2_ν of 1 during the fit and thus balance the different datasets in the MCMC.

The resulting fit (Fig. 1) has a χ^2 of 176 ($\nu = 68$) for the radial-velocity data (calculated without added jitter), which likely indicates that stellar activity is affecting the radial-velocities, and that there are non-uniformities on the face of the star during the transit. Note that WASP-19 has shown star spots during transits (Southworth, unpublished data), that the star shows a rotational photometric modulation at 10.5 d (Hebb et al. 2010), and also that the most discrepant HARPS point during transit (at phase 1.032) was taken 31 days prior to the main HARPS transit. Further, the size of the residuals is in line with that expected from activity in spotted G stars (Saar & Donahue 1997). The fit to the NTT transit lightcurve has a χ^2 of 69 ($\nu = 70$).

4. Results and Discussion

We find that WASP-19b is in an aligned orbit, with $\lambda = 4.6 \pm 5.2^\circ$, where λ is the angle between the planet’s orbit and the sky-projected stellar rotation axis. Further we find that the eccentricity is compatible with zero, with a 1- σ upper limit of 0.009 and a 3- σ upper limit of 0.02.

Hebb et al. (2010) reported a rotational modulation in the WASP data at a period of 10.5 ± 0.2 d. With the stellar radius from Table 2 this would translate to an equatorial velocity of $4.77 \pm 0.13 \text{ km s}^{-1}$. This estimate of v is compatible both with our spectroscopic $v \sin I$ of $5.0 \pm 0.3 \text{ km s}^{-1}$ and with the $v \sin I$ fitted to the R–M of 4.6 ± 0.3

Table 2: System parameters for WASP-19.

Parameter (Unit)	Value
P (d)	0.7888400 ± 0.0000003
T_c (HJD)	$2455168.96801 \pm 0.00009$
T_{14} (d)	0.0655 ± 0.0003
$T_{12} = T_{34}$ (d)	0.0135 ± 0.0005
$\Delta F = R_P^2/R_*^2$	0.0206 ± 0.0002
b	0.657 ± 0.015
i ($^\circ$)	79.4 ± 0.4
K_1 (km s^{-1})	0.257 ± 0.003
γ (km s^{-1})	20.7873 ± 0.0002
$e \cos \omega$	0.0024 ± 0.0020
$e \sin \omega$	0.000 ± 0.005
e	$0.0046^{+0.0044}_{-0.0028}$ < 0.02 (3σ)
ω ($^\circ$)	3 ± 70
$\phi_{\text{mid-occult}}$	0.5015 ± 0.0012
$v \sin I$ (km s^{-1})	4.63 ± 0.26
λ ($^\circ$)	4.6 ± 5.2
ψ ($^\circ$)	< 20 (2σ)
M_* (M_\odot)	0.97 ± 0.02
R_* (R_\odot)	0.99 ± 0.02
$\log g_*$ (cgs)	4.432 ± 0.013
ρ_* (ρ_\odot)	$0.993^{+0.047}_{-0.042}$
M_P (M_{Jup})	1.168 ± 0.023
R_P (R_{Jup})	1.386 ± 0.032
$\log g_P$ (cgs)	3.143 ± 0.018
ρ_P (ρ_J)	0.438 ± 0.028
a (AU)	0.01655 ± 0.00013
$T_{P,A=0}$ (K)	2050 ± 40

km s^{-1} . That match implies that the stellar spin axis is nearly perpendicular to the line of sight, which suggests that not only is λ low but that the obliquity itself, ψ , is also low. Since the impact factor ($b = 0.66$) is relatively high, the R–M value will sample higher latitudes and thus might be reduced by differential rotation. We therefore take the spectroscopic $v \sin I$ as a better indicator of the projected equatorial velocity. That results in a 2σ limit of $I > 65^\circ$, which translates (using information from Table 2 and equation 9 from Fabrycky & Winn 2009) to a 2σ upper limit of $\psi < 20^\circ$.

The known hot Jupiter exoplanets show a ‘pileup’ around periods of 3–4 d (e.g. Szabó & Kiss 2011). The smaller number at longer periods (~ 10 d) is to some extent a selection effect, resulting from the limited time sampling of ground-based

transit surveys. The candidate list for Jupiter-sized objects from the better-sampled *Kepler* data shows proportionately more at longer periods, but still shows a peak at 3–4 d and a decline beyond that (Borucki et al. 2011). The reduced number at periods below 2 d is definitely real, being seen in both ground- and space-based transit surveys and in radial-velocity surveys. For example the frequency of Jupiter-sized *Kepler* candidates drops by more than an order of magnitude below semi-major axis ~ 0.03 AU (period ~ 2 d) (Borucki et al. 2011), and note that this is a lower limit to the fall-off of planets, since as the planets become rarer the transit-mimics would become a larger fraction of the candidates.

Similarly, the WASP-South survey, which has found the 3 known Jupiter-sized planets with periods < 1 d (WASP-18b, Hellier et al. 2009; WASP-19b, Hebb et al. 2010; WASP-43b, Hellier et al. 2011), shows a much reduced ‘hit rate’ for planets below 2 d (Hellier et al. 2010), even though it will be most sensitive to such planets, since they produce the most transits and also because the transit durations are shorter compared to the data lengths. Thus the transiting Jupiters with periods below 1 d are rare, and found only because the WASP survey covers more than an order of magnitude more stars than *Kepler*.

Note, further, that this means that the actual frequency of such planets (not just transiting ones) will be lower still, since the range of inclinations that produces a transit rises steeply for decreasing semi-major axis for such close-in planets. For example WASP-19b would transit for inclinations $> 74^\circ$, but, if it were in the pileup near 3–4 d, the limit would be $\sim 85^\circ$, a factor 3 reduction in probability. Thus a tentative estimate is that planets such as WASP-19b are two orders of magnitude less common than hot-Jupiters at 3–4 d. This means that either Jupiter-sized planets cannot easily get into such orbits, or that something, such as tidal orbital decay, is then rapidly destroying them.

Ford & Rasio (2006) noted that the lower edge of the hot-Jupiter pileup was near twice the Roche limit, whereas disc migration would be expected to produce a smooth distribution down to the Roche limit. They argued that this would arise naturally if many hot Jupiters arrived from much further out by being scattered into highly eccentric

orbits that were then circularised while conserving angular momentum. The finding of many misaligned and retrograde planet orbits among those in the pileup (Triaud et al. 2010; Winn et al. 2010; Narita et al. 2010) also argues that these systems (or a large fraction of them) arise not from simple migration, but from third-body process such as planet–planet scattering or the Kozai mechanism (e.g. Fabrycky & Tremaine 2007; Nagasawa et al. 2008; Triaud et al. 2010).

However, there are 5 hot Jupiters further in than 2 Roche radii (see Matsumura et al. 2010), of which WASP-19b is the most extreme. Using the parameters of Table 2, WASP-19b, with an orbital period of 0.79 d, has a semi-major axis of only 1.21 times the Roche tidal radius ($a_R \approx 2.16 R_P (M_*/M_P)^{1/3}$). Guillochon et al. (2010) argue that such orbits are unlikely to result from the scattering of planets from outside the ice line, followed by circularisation, since the planets would instead be destroyed or ejected. Thus they argue that these planets must have migrated inwards prior to scattering, or have spiralled inwards after scattering as a result of tidal decay.

Given that the tidal decay timescale for WASP-19b in its current orbit is likely to be significantly shorter than the system age, we suggest, following Matsumura et al. (2010) and Guillochon et al. (2010), that the most likely scenario for WASP-19b is: formation beyond the ice line; transfer to an orbit near $2a_R$, at the short-period edge of the hot-Jupiter ‘pileup’, by scattering or by the Kozai mechanism, followed by circularisation at $2a_R$; and then tidal decay of the orbit to the current $1.2a_R$.

The timescale for tidal decay of the orbit is set by the tidal dissipation in the star, denoted by the stellar quality factor Q'_* , while the eccentricity damping is also affected by the planetary dissipation, Q'_P , and so could proceed faster, allowing circularisation at $2a_R$ before significant decay of the orbit (Matsumura et al. 2010). To investigate whether this scenario is consistent with the observed parameters of WASP-19b we need a value of Q'_* small enough such that WASP-19b’s orbit will decay from $\sim 2a_R$ to $1.2a_R$ within the lifetime of WASP-19, estimated at $\gtrsim 1$ Gyr by Hebb et al. (2010), yet large enough to result in a long-enough lifetime of WASP-19b to give a reasonable probability of now observing it.

Using eqn 5 of Levrard et al. (2009)¹ we find that to have decayed inwards from $2a_R$ within 1 Gyr would require a Q'_* no higher than 10^7 , while a 10-Gyr age would allow up to 10^8 (though note that we also need time for the third-body interactions leading to the starting point of $\sim 2a_R$). Using the same equation the remaining lifetime would be 40 Myr for $Q'_* = 10^7$, thus giving a $\sim 4\%$ probability of catching the planet in its current state. This probability is in line with the much smaller number of Jupiters below 1 d compared to at 3–4 d.

While the range $Q'_* = 10^7$ – 10^8 is much higher than values taken from binary stars, Penev & Saselov (2011) argue that, since stars are not spun up by planetary-mass companions, the tidal forcing by planets does not resonate with stellar tides, and thus that dissipation is much lower than in binary stars, and hence Q'_* can be as high as 10^9 .

According to Matsumura et al. (2010) the obliquity would be damped on a similar timescale to the orbital decay, and the eccentricity would be damped on either the same or a faster timescale (depending on Q'_P). Thus this scenario of significant orbital decay is consistent with our finding of λ , ψ and e compatible with zero, even if these were previously larger during the evolution to and at $2a_R$. Winn et al. (2010) have argued that planets around cool stars with significant convection zones ($T_{\text{eff}} < 6250$ K) will rapidly evolve to aligned orbits, and this fits with WASP-19's T_{eff} of 5500 K.

Note that it is harder to find a plausible scenario if we start the infall from larger orbital separations. Given the steep dependence of timescale on a ($\tau \propto (a/R_*)^5$; Levrard et al. 2009), a small enough Q'_* to fit within the age would then produce a very small probability of finding it in its current orbit. For this reason, it is hard to explain WASP-19b's orbit by disc migration and tidal decay alone: if these processes were efficient enough to have moved WASP-19b that far inwards, the same processes would likely have destroyed it.

The other possibility outlined by Guillochon et al. (2010) is that WASP-19b first migrated inwards to well within the ice line and was then scattered to its present semi-major axis. This requires

a lot of fine tuning to produce a as small as $1.2a_R$. The maximum radius at scattering can be only 0.01 of the ice line (Guillochon et al. 2010), the eccentricity after scattering must not be too high, and one has to avoid destruction by tidal orbital decay; yet if there hasn't been significant tidal decay then one could expect relics of the scattering in the form of eccentricity or misalignment. Thus our findings of an aligned, circular orbit make this already unlikely scenario even less likely.

Thus, the current orbit of WASP-19b, the tightest of the known exoplanets, is most plausibly explained if the planet first moved to near $\sim 2a_R$ by scattering or by the Kozai mechanism, as has been suggested for many of the hot Jupiters in the 3–4-d pileup, and circularised there; and then, perhaps through starting at the lower edge of the pileup, spiralled inward to its current location by orbital decay.

Based on observations made with the ESO 3.6-m/HARPS, program 084-C-0185, and the ESO NTT, and the Euler 1.2-m at La Silla Observatory.

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¹See Matsumura et al. (2010) for corrections to some of the equations in this paper.

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